Modeling and control of two five-phase induction machines connected in series powered by matrix converter

Mohamed Nekkaz, Abdelkader Djahbar, Rachid Taleb
Laboratoire Génie Electrique et Energies Renouvelables (LGEER), Electrical Engineering Department, Hassiba Benbouali University of Chlef, Algeria

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ABSTRACT

The two five-phase Induction Motor (IM) drive system that is serially connected is available in literature. The power supply of such system is considered as a matrix converter (a direct AC to AC converter system) by three and five-phases outputs. The main benefit from the drive topology is the sinusoidal source as a side current with a controllable input side power factor. The decoupled control is achieved similarly to the inverter based drive system. In this paper; the decoupled control of two five-phase induction machines serially connected and powered by a five-phase matrix converter as well as analytical and simulation results are presented.

Corresponding Author:

Mohamed Nekkaz
Electrical Engineering Department
Hassiba Benbouali University of Chlef
Laboratoire Génie Electrique et Energies Renouvelables (LGEER)
BP. 78C, Ouled Fares 02180, Chlef, Algeria
Email: nekkaz_mohamed@yahoo.fr

1. INTRODUCTION

The three-phase induction machines are reported to have eminent recognized benefits including low maintenance, reliability, simple construction, ruggedness, off-shelf availability as well as cheaper cost which explain their widespread applications in numerous industries [1]. Furthermore, with the appearance of fast and cheap power electronic switching gadgets, the control of induction machines became flexible and easier in addition to the number of its phases that can be considered as a designed parameter that might be diverse.

The multi-phase motors (superior to three-phase) were extensively researched in literature. It has been found that they have multiple benefits compared to three-phase machines, for instance, reduced torque pulsations [2], [3], high density of torque [4], [5], stability and fault tolerance [6], [7] along low ripple current [8]. Therefore, multi-phase order machines are usually appraised for niche application areas like electric/hybrid electric vehicles, ship propulsion, robotics and electric aircraft. Exhausted reviews on the research development of multi-phase motors are proposed in [9, 10].

One of the applications of multi-phase machines is their parallel connection and/or series connection. This drive system is called a series-connected/parallel-connected two-motor drive system. This drive system is allocated from a variable frequency and variable voltage supply (most commonly a power electronic inverter) introduced in [11], [12]. The drive system is such that the motors are controlled independently and can carry different loads, can run at different speeds without interfering with each other.

The type of machines applied in the drive topology is also not specific [13]. The machines are controlled using the vector control approach.

Considering that the vector controls of multi-phase motors need two stator current components thus, the additional stator current component is applied to control additional motors [14]. So, by connecting in series the multi-phase stator windings it will be possible to independently control every machine with supply appearing as an individual multi-phase voltage source inverter [15]. A particular drive system that is immersed by this concept is the parallel-connected/five-phase series two-motor drive, comprising the two five-phase motors and provided by an individual five-phase voltage source inverter. This topology was analyzed in substantial detail in [16], [17]. The multi-motor drive systems are disputed up to the present in the literature with the use of their supply of multi-phase voltage source inverter; however, the matrix converter was not tested for the drive of such topology.

This present paper deals with the feasibility of driving a five-phase series-connected two-motor drive system with a direct AC to AC converter (matrix converter) [18]. The originality of this work lies in the new solution of using a matrix converter for feeding two-motor drive topology by using modulation that produces two significant frequency outputs from the matrix converter in order to control the two series-connected five-phase motors. It is shown that the drive topology can be fed successfully using a matrix converter [19]. The advantage that is offered by this solution is sinusoidal source side current, no use of bulky DC link capacitors, controllable power factor and two-way power flow. The downside of this scheme is the complex system with a large number of bi-directional power semiconductor switches [20]. The output voltage is lower compared to the inverter-based system [21]. An analytical approach was used in this work to advance and study the suggested modulation techniques with additional support by simulation results.

2. MODELING OF A FIVE-PHASE MATRIX CONVERTER

The topology of power circuits of three to five-phase matrix converters is represented in Figure 1. The input is a three-phase fixed frequency supply over the grid system (50 Hz and 220 V) as well as fixed voltage. The output is n-phase with variable frequencies and voltages. A tiny filter is needed at the input source side and the switches are bi-directional for allowing regenerative operation of the load. The matrix converter is modulated both using a carrier-based Pulse Width Modulation (PWM) [3] and Space Vector PWM (SVPWM) [22].

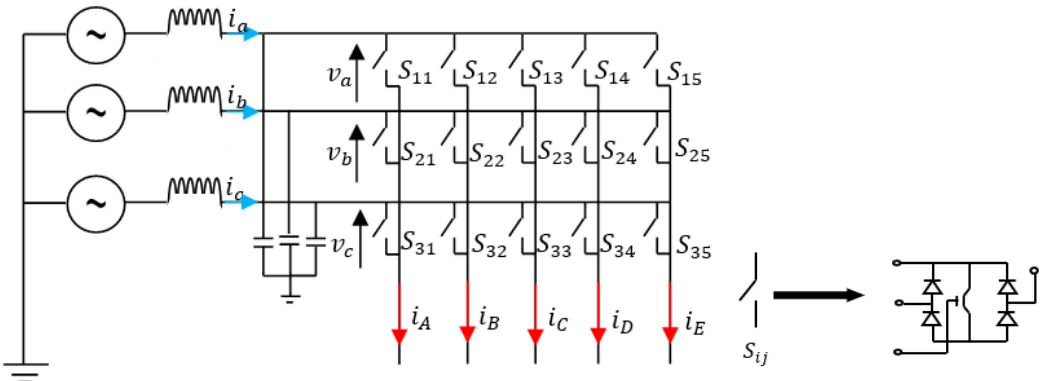

Figure 1. Principle diagram of the Pentaphasées matrix converter

The work presented here of a simple carrier-based PWM scheme is derived in [5]. However, the considered load was a simple R-L load. Furthermore, analytical treatments remained the same as that of [23] as the input side was a three-phase. Nevertheless, the output side increased to five and consequently, the investigation has been changed in order to fit the required number of the output phase. Thus, at the input, a three-phase system is supposed.

$$\begin{cases} v_a = |V| + \cos(\omega t) \\ v_b = |V| + \cos(\omega t - 2\pi/3) \\ v_c = |V| + \cos(\omega t - 4\pi/3) \end{cases} \quad (1)$$

Considering that the output voltages of the matrix converter are accompanied by a decoupled frequency from the input voltages, the duty ratios of the switches were consequently calculated. Thus, calculation of the desired five-phase output voltage duty ratios is done with a manner as the output voltage remains unconstrains of the input frequency. To put it differently, the three-phase input voltages could be regarded to be in a stationary reference frame while the five-phase output voltages may be regarded as in a synchronous reference frame hence, in output voltages, the expression of the input frequency is absent. In view of the above-mentioned information, a duty ratio of output phase j was selected as:

$$\begin{cases} \delta_{ai} = k_i + \cos(\omega t - \rho) \\ \delta_{bi} = k_i + \cos(\omega t - \frac{2\pi}{3} - \rho) \\ \delta_{ci} = k_i + \cos(\omega t - \frac{4\pi}{3} - \rho) \end{cases} \tag{2}$$

where ρ represents the phase shift at the input side and the input/output voltages are connected as:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \\ V_E \end{bmatrix} = \begin{bmatrix} \delta_{aA} & \delta_{bA} & \delta_{cA} \\ \delta_{aB} & \delta_{bB} & \delta_{cB} \\ \delta_{aC} & \delta_{bC} & \delta_{cC} \\ \delta_{aD} & \delta_{bD} & \delta_{cD} \\ \delta_{aE} & \delta_{bE} & \delta_{cE} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3}$$

So, the phase output voltage can be acquired applying the above-mentioned duty ratios as:

$$V_A = k_A|V|[\cos(\omega t) * \cos(\omega t - \rho) + \cos(\omega t - 2\pi/3) * \cos(\omega t - 2\pi/3 - \rho) + \cos(\omega t - 4\pi/3) * \cos(\omega t - 4\pi/3 - \rho)] \tag{4}$$

$$V_A = \frac{3}{2} * k_A|V|\cos(\rho) \tag{5}$$

The (5), $\cos(\rho)$ is used to indicate that the output voltage is impacted by ρ. k_A is described in equation (18). Therefore, V_A which is the output voltage is separated from the input frequency depending solely on the amplitude $|V|$ of the input voltage. k_A is a reference output voltage time-varying modulating signal for the output phase A including the wanted output frequency $\omega_{01} + \omega_{02}$, with ω_{01} representing the first fundamental output frequency of the machine-1 which is called also the operating frequency of machine-1 and ω_{02} is a second fundamental output frequency named also the operating frequency of machine-2. ω_{01} is stated as $m_1$whileω_{02} is stated as m_2. The five-phase reference output voltages may then be subsequently regarded as:

$$\begin{cases} k_{A1} = m_1 \cos(\omega_{01} t) \\ k_{B1} = m_1 \cos(\omega_{01} t - 2\pi/5) \\ k_{C1} = m_1 \cos(\omega_{01} t - 4\pi/5) \\ k_{D1} = m_1 \cos(\omega_{01} t - 6\pi/5) \\ k_{E1} = m_1 \cos(\omega_{01} t - 8\pi/5) \end{cases} \tag{6}$$

$$\begin{cases} k_{A2} = m_2 \cos(\omega_{02} t) \\ k_{B2} = m_2 \cos(\omega_{02} t - 2\pi/5) \\ k_{C2} = m_2 \cos(\omega_{02} t - 4\pi/5) \\ k_{D2} = m_2 \cos(\omega_{02} t - 6\pi/5) \\ k_{E2} = m_2 \cos(\omega_{02} t - 8\pi/5) \end{cases} \tag{7}$$

and:

$$\begin{cases} k_A = k_{A1} + k_{A2} \\ k_B = k_{B1} + k_{B2} \\ k_C = k_{C1} + k_{C2} \\ k_D = k_{D1} + k_{D2} \\ k_E = k_{E1} + k_{E2} \end{cases} \tag{8}$$

Therefore, from (5), the output voltages are obtained as:

$$\begin{cases} V_A = \left[\frac{3}{2} * k_{A1}|V|\cos(\rho)\right]\cos(\omega_{01}t) + \left[\frac{3}{2} * k_{A2}|V|\cos(\rho)\right]\cos(\omega_{02}t) \\ V_B = \left[\frac{3}{2} * k_{B1}|V|\cos(\rho)\right]\cos\left(\omega_{01}t - \frac{2\pi}{5}\right) + \left[\frac{3}{2} * k_{C2}|V|\cos(\rho)\right]\cos(\omega_{02}t - 4\pi/5) \\ V_C = \left[\frac{3}{2} * k_{C1}|V|\cos(\rho)\right]\cos\left(\omega_{01}t - \frac{4\pi}{5}\right) + \left[\frac{3}{2} * k_{E2}|V|\cos(\rho)\right]\cos(\omega_{02}t - 8\pi/5) \\ V_D = \left[\frac{3}{2} * k_{D1}|V|\cos(\rho)\right]\cos\left(\omega_{01}t - \frac{6\pi}{5}\right) + \left[\frac{3}{2} * k_{B2}|V|\cos(\rho)\right]\cos(\omega_{02}t - 2\pi/5) \\ V_E = \left[\frac{3}{2} * k_{E1}|V|\cos(\rho)\right]\cos\left(\omega_{01}t - \frac{8\pi}{5}\right) + \left[\frac{3}{2} * k_{D2}|V|\cos(\rho)\right]\cos(\omega_{02}t - 6\pi/5) \end{cases} \tag{9}$$

The discussion on the addition of the common-mode voltage and subsequent enhancement of the modulation index is presented in [4].

3. FIVE-PHASE SERIES-CONNECTED TWO MOTOR DRIVE

Basic topology of five-phase series-connected two-motor drive systems is represented in the Figure 1. The variable frequency (VF) source is supplying a five-phase IM (Motor 1) whose stator windings are connected to another five-phase IM (Motor 2) through appropriate phase transposition. The rotors of the two machines are independent and are connected to different mechanical loads [24].

Consequently, of the phase transposition that is represented in Figure 2, the inverter phase voltages were connected to separate machine phase voltages by:

$$\begin{cases} v_A = v_{as1} + v_{as2} \\ v_B = v_{bs1} + v_{cs2} \\ v_C = v_{cs1} + v_{es2} \\ v_D = v_{ds1} + v_{bs2} \\ v_E = v_{es1} + v_{ds2} \end{cases} \tag{10}$$

Generally, although both machines are of a five-phase, they might be different and as a consequence, they might have different parameters. The index '1' stands for the 1st IM that is immediately connected to a five-phase inverter while the index '2' denotes the 2nd IM which is connected past the 1st machine throughout the phase transposition.

Thus, the voltage equation of the whole system is scripted in a compact matrix form as:

$$\underline{v} = \underline{R} * \underline{i} + \frac{d(\underline{L} * \underline{i})}{dt} \tag{11}$$

Where the 15^{th} order of the system is used and

$$\underline{v} = \begin{bmatrix} \underline{v}^{inv} \\ \underline{0} \\ \underline{0} \end{bmatrix}, \underline{i} = \begin{bmatrix} \underline{i}^{inv} \\ \underline{i}_{r1} \\ \underline{i}_{r2} \end{bmatrix}; \underline{v}^{inv} = [v_A v_B v_C\ v_D\ v_E]^T; \underline{i}^{inv} = [i_A i_B i_C\ i_D\ i_E]^T;$$
$$\underline{i}_{r1} = [i_{ar1} i_{br1} i_{cr1}\ i_{dr1}\ i_{er1}]^T; \underline{i}_{r2} = [i_{ar2} i_{br2} i_{cr2}\ i_{dr2}\ i_{er2}]^T$$

The decoupling transformation was applied to ease the phase-domain model. [25], [26] has given Clark's decoupling matrix in power-invariant transformation.

$$[c] = \sqrt{\frac{2}{5}} \begin{bmatrix} 1 & \cos(\alpha) & \cos(2\alpha) & \cos(3\alpha) & \cos(4\alpha) \\ 0 & \sin(\alpha) & \sin(2\alpha) & \sin(3\alpha) & \sin(4\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(6\alpha) & \cos(8\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & \sin(6\alpha) & \sin(8\alpha) \\ \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} \end{bmatrix} \tag{12}$$

By excluding the x-y, zero-sequence equation about the inverter as well as the zero-sequence equation for rotor windings, over the two five-phase series-connected machines, the complete d-q model in the stationary reference frame is written in the elaborated form as:

$$\begin{cases} V_d^{inv} = R_{s1} i_d^{inv} + L_{s1} \frac{di_d^{inv}}{dt} + L_{m1} \frac{di_{dr1}}{dt} + R_{s2} i_d^{inv} + L_{s2} \frac{di_d^{inv}}{dt} \\ V_q^{inv} = R_{s1} i_q^{inv} + L_{s1} \frac{di_q^{inv}}{dt} + L_{m1} \frac{di_{qr1}}{dt} + R_{s2} i_q^{inv} + L_{s2} \frac{di_q^{inv}}{dt} \\ V_x^{inv} = R_{s1} i_x^{inv} + L_{s1} \frac{di_x^{inv}}{dt} + R_{s2} i_x^{inv} + L_{s2} \frac{di_x^{inv}}{dt} + L_{m2} \frac{di_{\alpha r2}}{dt} \\ V_y^{inv} = R_{s1} i_y^{inv} + L_{s1} \frac{di_y^{inv}}{dt} + R_{s2} i_y^{inv} + L_{s2} \frac{di_y^{inv}}{dt} + L_{m2} \frac{di_{\beta r2}}{dt} \end{cases} \tag{13}$$

Corresponding rotor equations are:

$$\begin{cases} 0 = R_{r1} i_{dr1} + L_{m1} \frac{di_d^{inv}}{dt} + (L_{r1} + L_{m1}) \frac{di_{dr1}}{dt} + \omega_1 \big(L_{m1} i_q^{inv} + (L_{r1} + L_{m1}) i_{qr1}\big) \\ 0 = R_{r1} i_{qr1} + L_{m1} \frac{di_q^{inv}}{dt} + (L_{r1} + L_{m1}) \frac{di_{qr1}}{dt} - \omega_1 (L_{m1} i_d^{inv} + (L_{r1} + L_{m1}) i_{dr1}) \\ 0 = R_{r2} i_{dr2} + L_{m2} \frac{di_x^{inv}}{dt} + (L_{r2} + L_{m2}) \frac{di_{dr2}}{dt} + \omega_2 \big(L_{m2} i_y^{inv} + (L_{r2} + L_{m2}) i_{qr2}\big) \\ 0 = R_{r2} i_{qr2} + L_{m2} \frac{di_y^{inv}}{dt} + (L_{r2} + L_{m2}) \frac{di_{qr2}}{dt} - \omega_2 (L_{m2} i_x^{inv} + (L_{r2} + L_{m2}) i_{dr2}) \end{cases} \tag{14}$$

The electromagnetic torques are evaluated as:

$$\begin{cases} T_{r1} = P_1 L_{m1} (i_{dr1} i_q - i_d i_{qr1}) \\ T_{r2} = P_2 L_{m2} (i_{dr2} i_y - i_x i_{qr2}) \end{cases} \tag{15}$$

The mechanical equation of the two machines is described as:

$$\begin{cases} J_{m1} \frac{d}{dt} \Omega_1 = T_{r1} - T_{L1} - f_{m1} \Omega_1 \\ J_{m2} \frac{d}{dt} \Omega_2 = T_{r2} - T_{L2} - f_{m2} \Omega_2 \end{cases} \tag{16}$$

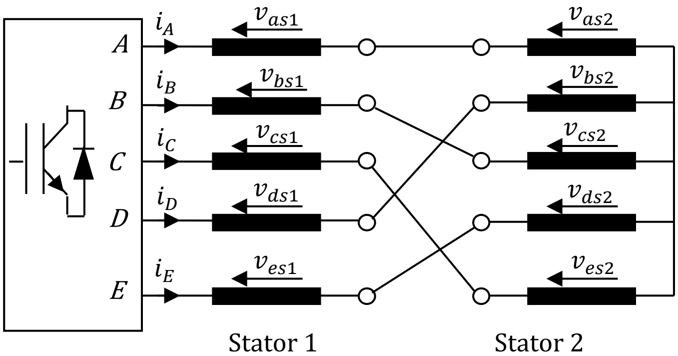

Figure 2. Representation of two five-phase IM in series with transposed stator phases

4. VECTOR CONTROL OF THE TWO-MOTOR DRIVE

As stated by (13)-(16), the phase transposition places the stator d−q axis windings of the 2nd machine in series connected with the x−y windings of the 1st machine (for example into the x−y subspace of the inverter). In addition, using standard indirect method of Rotor Flux Oriented (RFO) control, the independent vector control of the two machines can be achieved. For the indirect RFO controller for the two machines, it is of a similar structure in addition to an asymmetrical six-phase or three-phase machines [20]. Furthermore, as shown in Figure 3, only one difference is noted which is at the output, five instead of three-phase current references are established. The two indirect RFO controllers that function parallelly gave at the output phase current references (k $= \sqrt{2/5}$ of the two machines with references for x−y stator current components that are zero for both machines as given by Figure 3.

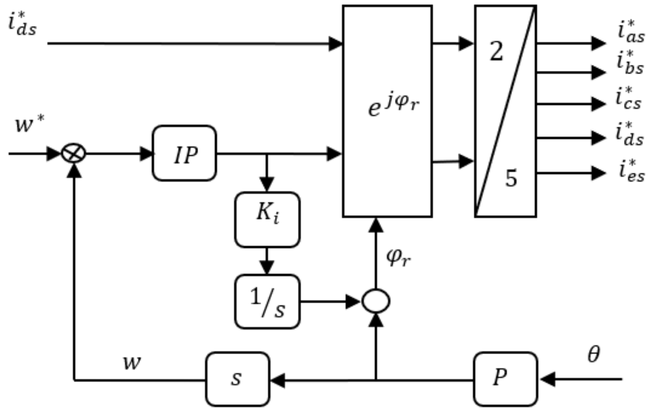

Figure 3. Indirect RFO controller for a five-phase induction machine ($k_1 = \frac{1}{T_r i_{ds}^*}$)

$$\begin{cases} i_{as1}^* = k\left(i_{ds1}^* cos\varphi_{r1} - i_{qs1}^* sin\varphi_{r1}\right) \\ i_{bs1}^* = k\left(i_{ds1}^* \, cos(\varphi_{r1} - \alpha) - i_{qs1}^* sin(\varphi_{r1} - \alpha)\right) \\ i_{cs1}^* = k\left(i_{ds1}^* \, cos(\varphi_{r1} - 2\alpha) - i_{qs1}^* sin(\varphi_{r1} - 2\alpha)\right) \\ i_{ds1}^* = k\left(i_{ds1}^* \, cos(\varphi_{r1} - 3\alpha) - i_{qs1}^* sin(\varphi_{r1} - 3\alpha)\right) \\ i_{es1}^* = k\left(i_{ds1}^* \, cos(\varphi_{r1} - 4\alpha) - i_{qs1}^* sin(\varphi_{r1} - 4\alpha)\right) \end{cases} \tag{17}$$

$$\begin{cases} i_{as2}^* = k\left(i_{ds2}^* cos\varphi_{r2} - i_{qs2}^* sin\varphi_{r2}\right) \\ i_{bs2}^* = k\left(i_{ds2}^* \cos(\varphi_{r2} - \alpha) - i_{qs2}^* sin(\varphi_{r2} - \alpha)\right) \\ i_{cs2}^* = k\left(i_{ds2}^* \cos(\varphi_{r2} - 2\alpha) - i_{qs2}^* sin(\varphi_{r2} - 2\alpha)\right) \\ i_{ds2}^* = k\left(i_{ds2}^* \cos(\varphi_{r2} - 3\alpha) - i_{qs2}^* sin(\varphi_{r2} - 3\alpha)\right) \\ i_{es2}^* = k\left(i_{ds2}^* \cos(\varphi_{r2} - 4\alpha) - i_{qs2}^* sin(\varphi_{r2} - 4\alpha)\right) \end{cases} \tag{18}$$

For the establishment of the overall inverter current references, the currents in (17) and (18) are summarized and the series connections with phase transposition are presented in Figure 3.

$$\begin{cases} i_A^* = i_{as1}^* + i_{as2}^* \\ i_B^* = i_{bs1}^* + i_{bs2}^* \\ i_c^* = i_{cs1}^* + i_{cs2}^* \\ i_d^* = i_{ds1}^* + i_{ds2}^* \\ i_E^* = i_{es1}^* + i_{es2}^* \end{cases} \tag{19}$$

In the frame of the stationary reference, the closed-loop phase current control is at the end used to force the proper inverter output currents of (2) in order to trace the reference currents of (19). Supposing that the idealistic current control is applied, one has the equivalence of the reference inverter currents (19) with the proper inverter currents (2) therefore, machine currents are connected with reference machine currents of (17) and (18) by:

$$\begin{cases} i_{as1} = i_{as2} = i_{as1}^* + i_{as2}^* \\ i_{bs1} = i_{cs2} = i_{bs1}^* + i_{bs2}^* \\ i_{cs1} = i_{es2} = i_{cs1}^* + i_{cs2}^* \\ i_{ds1} = i_{bs2} = i_{ds1}^* + i_{ds2}^* \\ i_{es1} = i_{ds2} = i_{es1}^* + i_{es2}^* \end{cases} \tag{20}$$

In consideration of the right-hand part of (19) that includes in a stable-state operation two sets of sinusoidal currents, generally distinct frequencies and amplitudes were added in accordance with the phase transposition that is shown in Figure 3. Following (19), each of the five-phases of any of the two-machines

carries at the same time two sinusoidal current components. Furthermore, one directs the flux/torque producing $(\alpha - \beta)$ components and the other is as a result of the other machine in series determining parasitic $(x - y)$ current components.

5. SIMULATION RESULTS

MATLAB/Simulink for the complete drive system was used for the developement of the simulation model. The three-phase grid supply was supposed as 50 Hz and 400 V rms phase voltage and since the two-motor drive was taken into account, the double voltage was assumed. For the 1st machine, the five-phase reference voltage was selected while for the 2nd machine, a different set of five-phase reference was chosen. The five-phase modulating signals were developed by including the two five-phase references as reported in the transposition rule (7).

The simulation condition is presented as;

Motor-1 working at 1500 rpm rated speed (reference frequency of 50 Hz) and Motor-2 working at half of rated speed of 750 rpm and a reference frequency of 50 Hz.

In the initial trial, the 1st machine operates at 1500 rpm then at -1500rpm at t=0.9s and the second machine was running at 750 rpm of the speed reference. The load torque that were applied to the first and second machines was 100 % of the rated torque at respectively $t_1 = [1 - 3]$ s and $t_2 = [1.5 - 3.5]$ s.

In the third test, the first machine was running at 1500 rpm then at -1500rpm at t=0.9s and the second machine speed reference was of 750 rpm. The load torque applied to the first machine was 100 % of the rated torque at $t_1 = [1 - 3]$ s. In addition, the first machine was running at 1500 rpm and for the second machine, it was 750 rpm, then -750 rpm at $t_2 = [1.5 - 3.5]$ s the speed reference of the 2nd motor. The load torque applied to the first and second machines is 100 % of the rated torque. It is evident from Figures (4, 5, 6 and 7) and Figures (8, 9, 10, 11, 12 and 13) that the loading step of the 2nd motor does not generate any disturbance in the 1st motor's speed and torque references traces.

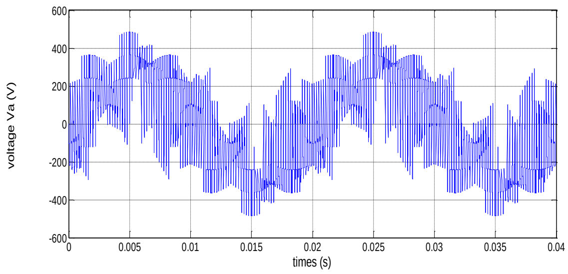

Figure 4. Output voltage Va (V)

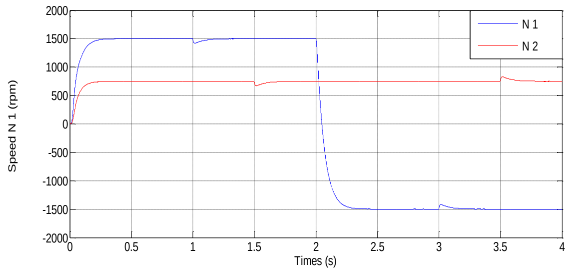

Figure 5. Speeds of the first and second machine

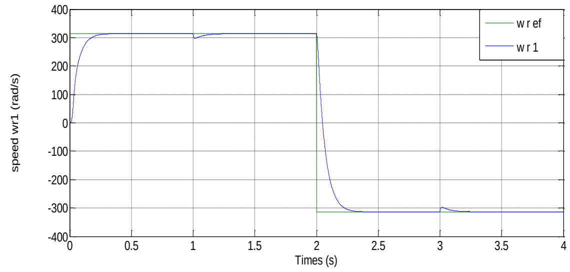

Figure 6. Speeds of the first machine Vs its reference value

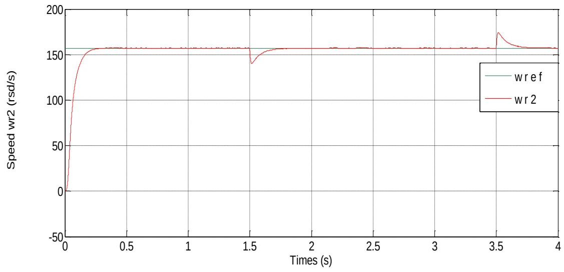

Figure 7. Speeds of the second machine Vs its reference value

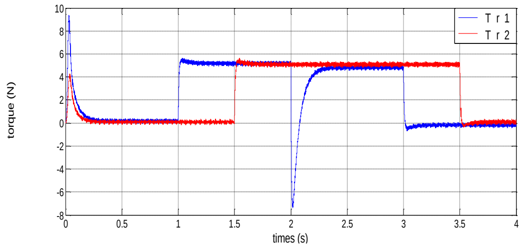

Figure 8. Torques of the first and second machines.

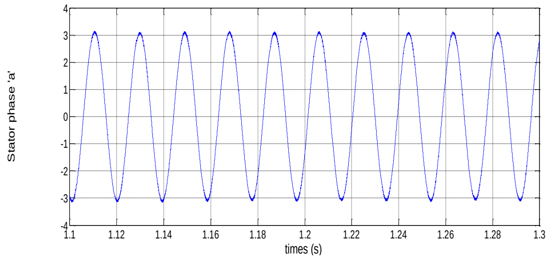

Figure 9. Currents is one phase of the first machines

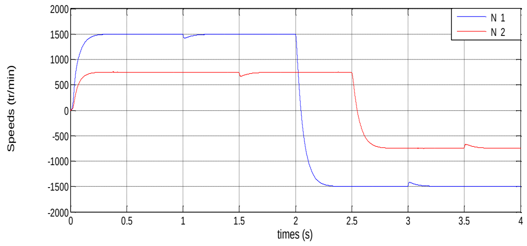

Figure 10. Speeds of the first and second machine

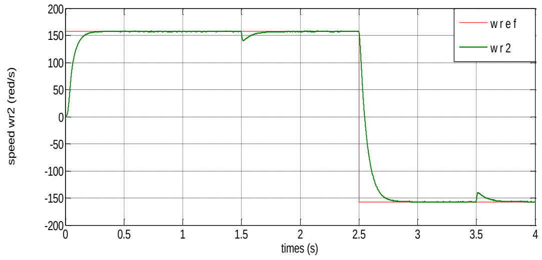

Figure 11. Speeds of the second machine Vs its reference value

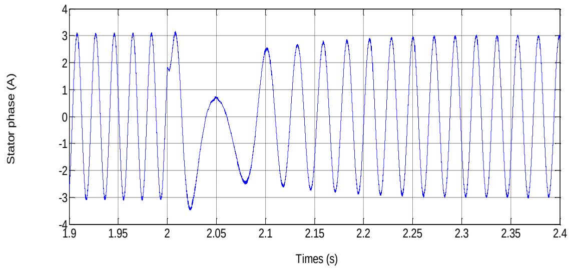

Figure 12. Currentis one phase of the firest machines

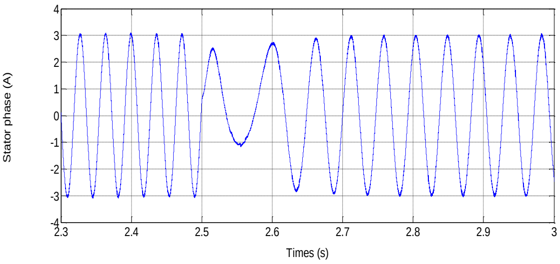

Figure 13. Currentis one phase of the second machines

6. CONCLUSIONS

Three to five-phases matrix converters based five-phase series-connected two-motor drive structure was presented in this paper. The carrier-based PWM techniques were used for the control of the matrix converter. The matrix converter successfully drives the two five-phase series-connected induction machines. This solution has an advantage of a higher power factor and sinusoidal source side current. We have obtained a completely decoupled control by the independent vector control, which allowed decoupling the flux control and the torque for the two machines, which leads to control several machines in series that can have polyphase machines of different types

SIMULATION PARAMETERS

Parameters	symbol	Values	Units
Stator resistance	R_s	6.3	Ω
Rotor resistance	R_r	10	Ω
Stator leakage inductance	L_{lS}	0.46	mH
Rotor leakage inductance	L_{lr}	0.46	mH
Mutual inductance	M	0.42	mH
Stator rated Frequency	f_s	50	Hz
Moment of Inertia	J_m	0.01	Kg.m^2
Number of Poles	P	2	
Rated Torque	T_r	5	Nm

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BIOGRAPHIES OF AUTHORS

Mohamed Nekkaz was born in Chlef, Algeria, inFebruary 1986, He received the Engineer and Masterdegrees in electrical engineering from the university hassiba ben bouali of Chlef, Algeria, in 2009 and 2012, respectively. He is a Ph.D. student in electrical engineering at university hassiba ben bouali of Chlef since 2013. His scientific work is related to electrical machines, and drives and Power Electronics. His present research interests include multi machine drives, degraded mode, matrix converter and power quality.
Email: Nekkaz_mohamed@yahoo.fr

Professor Abdelkader Djahbar was born in Chlef, Algeria, in February 1970. He received the Eng. and M.Sc. degrees in electrical engineering from the National Polytechnic school of Algiers, Algeria, in 1995 and 1998, respectively, and the Ph.D. degree in electrical engineering from the Mohamed Boudiaf University of Science and Technology of Oran (USTO), Algeria, in 2008 and the Habilitation to lead Researches in 2012 at the USTO University, Algeria. In December 2002, he joined the electrical engineering department of Hassiba Ben Bouali Univesity of Chlef, Algeria. Since August 2012, he is Associate Professor in the samedepartment. He is associate researcher in the LMOPS laboratory of the Université de Lorraine and Centrale Supélec since April 2014 and researcher at the LGEER laboratory of UHBC since 2013. His scientific work is related to electrical machines and drives and Power Electronics. His present research interests include multi machine drives, matrix converter and power quality. Email: a_djahbar@yahoo.fr

Professor Rachid Taleb received the M.S. degree in electrical engineering from the Hassiba Benbouali University, Chlef, Algeria, in 2004 and the Ph.D. degree in electrical engineering from the Djillali Liabes University, Sidi Bel-Abbes, Algeria, in 2011. Currently he is a professor with the Department of Electrical Engineering, Hassiba Benbouali University. He is a team leader in the LGEER Laboratory (Laboratoire Génie Electrique et Energies Renouvelables). His research interest includes intelligent control, heuristic optimization, control theory of converters and converters for renewable energy sources.
E-mail: rac.taleb@gmail.com